ELECTROPHORETIC DISPLAY WITH COMPRESSED MEMORY DATA

The present invention relates to a bi-stable display and, in particular, to a method and apparatus for improving the storage density of data used in such displays.

Display devices of this type are typically electrophoretic displays used, for example, in monitors, laptop computers, personal digital assistants (PDA's), mobile telephones and electronic books, newspapers, magazines, etc.

An electrophoretic display comprises an electrophoretic medium (electronic ink) containing charged particles in a fluid, a plurality of display elements (pixels) arranged in a matrix, first and second electrodes associated with each pixel, and a voltage driver for applying a potential difference to the electrodes of each pixel to cause charged particles to occupy a position between the electrodes, depending on the value and duration of the applied potential difference, so as to display an image or other information.

A display device of the type mentioned in the opening paragraph is, for example, known from international patent application WO 99/53373WO, published April 9, 1999, by E Ink Corporation, Cambridge, Massachusetts, US, and entitled Full Color Reflective Display With Multichromatic Sub–Pixels. That patent application discloses a display comprising two substrates, one of which is transparent. The other substrate is provided with electrodes arranged in rows and columns. A crossing between a row and a column electrode is associated with a display element or pixel. The display element is coupled to the column electrode via a thin-film transistor (TFT), the gate of which is coupled to the row electrode. This arrangement of display elements, TFT transistors and row and column electrodes jointly forms an active matrix. Furthermore, the display element comprises a pixel electrode. A row driver selects a row of display elements and the column driver supplies a data signal to the selected row of display elements via the column electrodes and the TFT transistors. The data signal corresponds to graphic data to be displayed.

Furthermore, electrophoretic ink is provided between the pixel electrode and a common electrode provided on the transparent substrate. The electrophoretic ink comprises multiple microcapsules of about 10 to 50 microns. Each microcapsule comprises positively charged white particles and negatively charged black particles suspended in a fluid. When a negative field is applied to the common electrode, the white particles move to the side of the microcapsule directed to the transparent substrate, and the display element becomes visible to a viewer. Simultaneously, the black particles move to the pixel electrode at the opposite side of the microcapsule where they

are hidden from the viewer. By applying a negative field to the pixel electrode, the black particles move to the common electrode at the side of the microcapsule directed to the transparent substrate, and the display element appears dark to a viewer. When the electric field is removed, the display device remains in the acquired state and exhibits a bi-stable character.

Recent developments in electrophoretic display technology focuses attention on improving the storage density of data used in such displays so as to achieve accurate greyscale reproduction. Greyscale in the display device images can be generated by controlling the amount of particles that move to the counter electrode at the top of the microcapsules. For example, the energy of the positive or negative electric field, defined as the product of field strength and time of application, controls the amount of particles moving to the top of the microcapsules to bring the display element to a desired optical state. It should be appreciated, however, that these displays are strongly influenced by image history, dwell time, temperature, humidity, lateral inhomogeneity of the electrophoretic foils, etc, all of which conspire to bring the display element to something other than the desired optical state. In particular, to offset these and other factors and bring a display element to a desired optical state, a matrix look-up table (LUT) or transition matrix is required. This matrix will have one dimension each for the desired final state, and for each of the other states (initial and any prior states). Depending upon the number of prior states to be considered, which can vary with the driving method, the look-up tables (LUTs) used may become very large. To take an extreme example, consider a process for a 256 (2^8) gray level electrophoretic display using an algorithm that takes account of an initial, final and two prior states. The necessary four-dimensional look-up table (LUT) has 2^{32} entries. If each entry requires 64 bits (8 bytes), the total size of the LUT would be approximately 32 Gbyte. Moreover, if the LUT were to then be compensated for temperature, it is then required to generate and store look-up-tables (LUT's) for different temperatures which are usually pre-determined, measured and stored in the display controller itself and in an external memory.

It is an object of the present invention to provide a display in which the storage limitations of the prior art are overcome.

It is a further object of the present invention to provide a display in which the storage density of data is improved.

A still further object of the present invention is to provide a display in which the improved storage density of data allows for accurate grey scale reproduction which considers one or more prior states of the device.

A further object of the present invention is to provide a display in which the improved storage density of data allows for accurate grey scale reproduction through compensation of temperature variations over a wide temperature range.

These and other objectives are achieved by the invention by providing a display including compression means for temporarily compressing incoming image information. The display further includes decompression means which decompress the temporarily compressed data, in a reverse operation, to generate necessary drive parameters. The display further includes a controller for retrieving waveform and time parameters from a look-up table and applying the waveform and time parameters to effect a change of the display elements from a current optical state to a predetermined next optical state in dependence upon the image information received in a current frame (N) and decompressed image information received in at least one prior frame (N-1) (e.g., alternative embodiments may consider two or more prior frames, N-2, N-3 and so on).

According to one aspect of the invention, the compression means used by the invention could be any well-known lossless or lossy compression algorithm. According to another aspect of the invention, the compression/decompression processes occur in a time interval which is insignificant relative to the time required to generate the necessary drive parameters in each frame.

The foregoing features of the present invention will become more readily apparent and may be understood by referring to the following detailed description of an illustrative embodiment of the present invention, taken in conjunction with the accompanying drawings, where:

FIG. 1 illustrates an electrophoretic display device 1 in conformance with a first embodiment of the invention; and

FIG. 2 illustrates an electrophoretic display device 1 in conformance with a second embodiment of the invention.

In the following description of embodiments of the present invention, reference is made to the accompanying drawings which form a part hereof, and in which is shown by way of illustration specific embodiments in which the invention may be practiced. It is to be understood that other embodiments may be utilized and structural changes may be made without departing from the scope of the described embodiments of the present invention.

Definitions

The term "grey state" or "grey scale" is used herein in its conventional meaning in the imaging art to refer to a state intermediate two extreme optical states of a pixel, and does not

necessarily imply a black-white transition between these two extreme states. For example, several of the patents and published applications referred to below describe electrophoretic displays in which the extreme states are white and deep blue, so that an intermediate "gray state" would actually be pale blue. Indeed, as already mentioned the transition between the two extreme states may not be a color change at all.

The terms "bistable" and "bistability" are used herein in their conventional meaning in the art to refer to displays comprising display elements having first and second display states differing in at least one optical property, and such that after any given element has been driven, by means of an addressing pulse of finite duration, to assume either its first or second display state, after the addressing pulse has terminated, that state will persist for at least several times, for example at least four times, the minimum duration of the addressing pulse required to change the state of the display element. It is shown in copending application Ser. No. 10/063,236, filed Apr. 2, 2002 (see also the corresponding International Application Publication No. WO 02/079869) that some particle-based electrophoretic displays capable of gray scale are stable not only in their extreme black and white states but also in their intermediate gray states, and the same is true of some other types of electro-optic displays. This type of display is properly called "multi-stable" rather than bistable, although for convenience the term "bistable" may be used herein to cover both bistable and multi-stable displays.

The discussion below concentrates upon one or more pixels of an electrophoretic display undergoing a gray scale transition, i.e., a change from one gray level to another, from an "initial" state to a "final" state. Obviously, the initial state and the final state are so designated only with regard to the transition being considered at a particular point in time and it is to be understood that the pixel has undergone transitions prior to the "initial" state and will undergo further transitions after the "final" state.

Where it is necessary to distinguish between multiple prior states, the term "first prior state" will be used to refer to the state in which the relevant pixel existed one (non-zero) transition prior to the initial state, the term "second prior state" will be used to refer to the state in which the relevant pixel existed one (non-zero) transition prior to the first prior state, and so on.

<u>Overview</u>

As described above, bi-stable displays act, to a first approximation, as impulse transducers, so that the final state of a pixel depends not only upon the electric field applied and the time for which this field is applied, but also upon the state of the pixel prior to the application of the

electric field. The state of the pixel prior to the present application of an electric field is the result of the pixel's image history, defined as the total energy (or stress), i.e., voltage x time, seen by each pixel over time.

As is well known to those in the display art, image information is provided to an electrophoretic display device in a series of consecutive frames, i.e., 1, 2, ..., N-1, N, N+1, N+2, and so on .... At each frame, a drive parameter (voltage x time) is generated for each display element of the display. The drive parameter is determined in part from the image information provided in the current frame N (i.e., current state) and the image history of the element for some number of prior states. In one embodiment, image information is considered from the current state (frame N) and one prior state (frame N-1) to generate the necessary drive parameters to effect a change of the display elements from a current optical state to a predetermined next optical state.

Generally, it is well known that bi-stable devices have a strong image history, and as a consequence, accurate grey scale reproduction requires data from as many prior states as possible. Further, when the device is compensated for temperature variations, the data requirements grow in proportion. As one example, to adjust a device for a temperature range of -22C to +80C with a ½ degree resolution, over two-hundred temperature compensation look-up tables are required. It is therefore apparent that the data requirements pose an enormous challenge in terms of minimizing the memory requirements and cost of a device.

By way of background, it is well known that many different data compression techniques exist in the prior art. Compression techniques can be divided into two broad categories, lossy coding and lossless coding.

A lossless compression technique compresses data without loss of the data so as to restore the compressed data to the original data, but there is a limit to a compression rate of the lossless compression algorithm. Thus, a lossless compression algorithm is generally employed in compressing a document file and a program file. (e.g., Huffman Coding, Run Length Encoding, LZW, etc.)

Conversely, a lossy compression technique compresses data by deleting relatively insignificant parts of the data, thereby decreasing the size of the data. Thus, the compression rate of the lossy compression algorithm is much higher than the compression rate of the lossless compression algorithm, but it is impossible to perfectly restore compressed data to the original

data. Thus, the lossy compression algorithm is generally employed in compressing audio and video files. (e.g., JPEG, MPEG, etc.).

In addition to the well known compression schemes, the invention also contemplates the use of a low-complexity scalable image compression algorithm based on the 8x8 block discrete cosine transform (DCT). Unlike a conventional DCT compression algorithm, the low-complexity scalable image compression algorithm uses no additional quantization or entropy. For a fuller discussion of this algorithm, "Low-Complexity Scalable Image Compression", Rene J. van der Vleuten, Richard P. Kleihorst, which is incorporated by reference.

First Embodiment

FIG. 1 illustrates an electrophoretic display device 1 in conformance with a first embodiment of the invention. The display device 1 of FIG. 1 includes a frame memory 9, a compression unit 3, a decompression unit 5, a display controller 7, a memory for storing a look-up table 12, a temperature sensor 13 and a display device 15 comprised of a plurality of electrophoretic display elements 18. The display device 1 performs real time data compression/decompression on receive image information (frame data), as will be described.

With continued reference to FIG. 1, in operation, image information (frame data) is provided to the electrophoretic display device 1 in a series of consecutive frames, i.e., 1, 2, .., N-1, N, N+1, N+2,... and so on, at successive time intervals. For example, frame data for the N-1th frame is received and processed at time T_{-1}; then in successive order, frame data for the Nth frame is received and processed at time interval T_0; frame data for the N+1th frame is received and processed at time T_{+1} and so on.

For ease of explanation, the process will be described in greater detail starting at time T_0 at which point the Nth frame data is received at input node 2 and processed by the electropheretic display device 1.

At time T_0, frame data associated with the current frame, referred to hereafter as Nth frame data, is received at input node 2 of the display device 1. The Nth frame data is processed substantially simultaneously in two ways. First, the Nth frame data is supplied to the compression unit 5 under control of the display controller 7. The compression unit 5 processes the Nth frame data and outputs compressed Nth frame data to be stored in the frame memory 9 under control of the display controller 7.

Second, substantially simultaneous with the operation of compressing and storing the Nth frame data, the display controller 7 is further arranged to use the Nth frame data, and data

corresponding to at least one prior state, to generate drive parameters 20 to effect a change of the display elements from a current optical state (first gray scale or color value) to a predetermined next optical state (second gray scale or color value).

In one embodiment, the necessary drive parameters 20 are derived in dependence on the current N^{th} frame data and one prior state, i.e., the $(N-1)^{th}$ frame data received in the previous frame, i.e., at time T_{-1}. It is noted that in order to utilize the $(N-1)^{th}$ frame data, it must first be retrieved from memory 9, where it has been previously stored in compressed form in the previous time interval, and decompressed by decompression unit 5 under control of the display controller 7.

As described above, in the present exemplary embodiment, display controller 7 is arranged to generate the drive parameters 20 (waveform and time parameters) for the display elements 18 in dependence upon the image information received in the current frame, N^{th} frame data, and the stored frame data (image information) corresponding to one previous state, $(N-1)^{th}$ frame data. Each state corresponds to a 4-bit number corresponding to a 16-level grey scale. These bits together form an 8 bit entry in the LUT 12. Preferably, the LUT 12 has address entries corresponding to at least one previous state of the display element and the current state of the display elements.

It is to be appreciated that in alternate embodiments, the waveform and time parameters may be generated in dependence upon additional prior states. For example, the drive parameters 20 may be generated in dependence on the N^{th} frame data received at time T_0, and two prior states, i.e., the $(N-1)^{th}$ and $(N-2)^{th}$ frame data received at respective time intervals T_{-1} and T_{-2}. It is noted that at time T_0, the $(N-1)^{th}$ and $(N-2)^{th}$ frame data have been previously stored in the frame memory 9 in compressed form at respective times T_{-1} and T_{-2}. The previously stored frame data and must first be decompressed for use in determining the necessary drive parameters 20 at time T_0. In addition to decompressing the required frame data, the present invention further conserves frame memory 9 by adding and deleting frames at each frame in accordance with a last-in-first-out (LIFO) protocol. For example, at time T_0, frame (N) data is stored in compressed form in the frame memory 9 and the least most recently added frame, frame (N-2) data, in the illustrative example, is purged from the frame memory 9. It is further noted, while the frame (N-1) data is decompressed for use at this time, it is not purged from the frame memory 9 until the next time interval T_{+1} in LIFO like manner.

Those of skill in the art will appreciate that for the compression/decompression processes described herein, it is possible to have near lossless compression and decompression. However,

in the preferred embodiment, some controlled loss is accepted in order to further optimize the process (e.g., avoid adding precision that would not result in better image display quality, as perceived by the user).

As shown in FIG. 1, the display device 1 also includes a digital temperature sensor 13 for sensing an operating temperature of the device and for providing a temperature compensation in order to reduce the temperature dependency of the grey value reproduction of the display device. To this end, the temperature sensor 13 generates, for example, a 4-bit number representing an actual operating temperature of the display device, and the address entry of the LUT 12 is extended with additional bits. It is noted that while the LUT 12 is shown in a separate memory 11, it can be realized in the same memory as the frame memory 9 in certain embodiments.

Table I is provided to further illustrate the method of the invention for compressing/decompressing frame data at each frame and generating the necessary drive parameters therefrom.

Reference is made to the second row of Table I. At time T_0, data received in the current frame (N), i.e., frame (N) data, is received at input node 2. At this time, the frame (N) data is stored in the memory 11, in compressed form (second column), and is also used substantially simultaneously as received (i.e., in uncompressed form), to generate the necessary drive parameters 20 to effect a change of the display elements 18 from a current optical state to a predetermined next optical state. It is noted that, in the illustrative embodiment, the drive parameters 20 are generated in dependence on both the frame (N) data and frame data corresponding to at least one prior state, i.e., frame (N-1) data (column 4). Substantially coincident with the operations described, frame (N-2) data is purged from the memory 9 in accordance with the LIFO protocol (column 3).

Table I.

Time	Received data	Stored data (in compressed form)	Purged frame data	Frame data required to generate necessary drive parameters
T_{-1}	N-1th frame data	N-1th frame data	N-3th frame data	N-1th frame data N-2th frame data
T_0	Nth frame data	Nth frame data	N-2th frame data	Nth frame data Frames N-1th frame data
T_{+1}	N+1th frame data	N+1th frame data	N-1th frame data	N+1th frame data

				Nth frame data Frames

The generated drive parameters 20 may consist of pulses of fixed duration and varying amplitude, pulses with a fixed amplitude, alternating polarity and a varying duration between two extreme values, and hybrid drive signals wherein both the pulse length and the amplitude can be varied. For a pulse amplitude drive signal, this predetermined drive parameter indicates the amplitude of the drive signal including the sign thereof. For a pulse time modulated drive signal, the predetermined drive parameter indicates the duration and sign of the pulse making up the drive signal. For a hybrid generation or pulse-shaped drive signal, the predetermined drive parameter indicates the amplitude and the length of portions making up the drive pulse. The predetermined drive parameter may be, for example, an 8-bit number. For each entry in the look-up table 12, the drive parameter is experimentally determined for a selected type of electronic ink for a corresponding grey level transition and different predetermined operating temperatures.

Second Embodiment

Yet another embodiment of the invention is shown in FIG. 2. In the present embodiment, in addition to compressing image information to improve memory storage density, the present embodiment compresses the look-up table data (LUT) 12 to achieve further memory storage density.

As shown in FIG. 2, the display 1 includes all of the elements of the display of FIG. 1 and further includes a second compression unit 15 and a second decompression unit 17, which respectively compress and decompress the look-up table data. It is noted that because the look-up table data constitutes a smaller percentage of the overall data requirements of the display 1, the improved storage density realized by compressing the look-up data is not as significant as compressing the voluminous frame data (image information) described in the previous embodiment.

It is further noted that alternative embodiments may utilize a plurality of look-up tables, instead of the single LUT 12 shown, to compensate for wide temperature variations which may be experienced by the device 1. For example, to adjust the device 1 for a temperature range of -22C to +80C with a ½ degree resolution, over two-hundred temperature compensation look-up tables (LUTs) are required. The plurality of temperature compensation LUTs may be preferably stored in compressed form in the memory 11. In use, upon determining the temperature of the display device 1, the LUT 12 from among the plurality of stored LUTs corresponding to the

detected temperature of the device 1 is identified, decompressed and used to generate the drive parameters 20 in the manner described above under control of the display controller 7.

It is noted that in each of the embodiments, the compression and decompression units 3, 5, 15 and 17 can be incorporated into the display controller 7. That is, the functionality of the compression and decompression units may be incorporated into the display controller, thereby removing the need to utilize stand-alone devices, as described in the previous embodiments.

Conclusion

In conclusion, as will be evident from the above description, the electrophoretic display device, in accordance with embodiments of the invention, improves the storage density of data used in such display devices. Further, the time required to perform the compression/decompression processes are insignificant relative to the operation of generating drive parameters in each consecutive frame. By compressing image information and/or LUT data in the device, accurate grey scale reproduction may be achieved at a reasonable cost.

Finally, the above-discussion is intended to be merely illustrative of the present invention and should not be construed as limiting the appended claims to any particular embodiment or group of embodiments. For example, the controller 7 may be a dedicated processor for performing in accordance with the present invention or may be a general-purpose processor wherein only one of many functions operates for performing in accordance with the present invention. The processor may operate utilizing a program portion, multiple program segments, or may be a hardware device utilizing a dedicated or multi-purpose integrated circuit. Each of the systems utilized may also be utilized in conjunction with further systems. Thus, while the present invention has been described in particular detail with reference to specific exemplary embodiments thereof, it should also be appreciated that numerous modifications and changes may be made thereto without departing from the broader and intended spirit and scope of the invention as set forth in the claims that follow. The specification and drawings are accordingly to be regarded in an illustrative manner and are not intended to limit the scope of the appended claims.

In interpreting the appended claims, it should be understood that:

a) the word "comprising" does not exclude the presence of other elements or acts than those listed in a given claim;

b) the word "a" or "an" preceding an element does not exclude the presence of a plurality of such elements;

c) any reference numerals in the claims are for illustration purposes only and do not limit their protective scope;

d) several "means" may be represented by the same item or hardware or software implemented structure or function; and

each of the disclosed elements may be comprised of hardware portions (e.g., discrete electronic circuitry), software portions (e.g., computer programming), or any combination thereof.